# Sculpting metals for anomalous transmission phenomena, complex waves and negative refractive metamaterials: underlying physics and applications

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## Abstract

In this talk, the potential of controlling the electromagnetic propagation by periodically-textured surfaces is reviewed. It is shown that backward-wave- and slow-wave-propagation, superluminal, effective negative refractive index and highly-confined complex surface waves are obtained with these metallic surfaces. The role of periodicity, complex surface waves and resonant-electric-coupling in all these phenomena is emphasized and compared against equivalent circuit models. The explanation of the underlying physics is combined with exemplary applications focused on the millimetre- and submillimetre-wave band.

## Introduction

Over the last few years we have seen dramatic advances in controlling the propagation of electromagnetic waves. The two main fields in this direction are metamaterials [1] and plasmonics [2]. Metamaterials took off at the beginning of the 21$^{st}$ century as a result of the experimental realization of a double-negative medium [3] and the firestorm of controversy brought by the perfect lens concept [4]. Nowadays, there is a race toward low-loss and high frequency metamaterials. On the other hand, the inflection point on plasmonics research was extraordinary (optical) transmission, which was brought to attention in the seminal paper of Ebbesen *et al.* [5]. Equally, extraordinary transmission has revitalized the field of gratings, which traces back more than a century ago. The recent convergence of both fields - metamaterials and plasmonics - via extraordinary transmission [6 ,7] has sparked considerable excitement since it has made it possible to proof experimentally negative refraction by double-negativity at high frequencies [8, 9].

The aim of this talk is threefold: firstly, to show a thorough analysis of subwavelength aperture arrays exhibiting not only extraordinary transmission, but also other unusual transmission or reflection features (either in the phase or magnitude response) when more complex systems are considered. For instance, when compound periods are contemplated [10], additional complex surface waves are generated by dielectric loading of the array which can interact with the modes supported by the arrays [11] or Babinet’s concepts are applied [12]; secondly, to bring the attention to patterned metals with more complex topologies such as complementary-split-ring-resonators [13] for enhanced field confinement [14]; thirdly, to exploit subwavelength hole arrays to achieve low-loss double negative and negative-positive birefringent metamaterials at millimetre and submillimetre-waves [8, 15]. All these will be pedagogically explained taking advantage of multitude tools: equivalent circuit models, grating theory, modal analysis, dispersion diagram, retrieved constitutive parameters, field distribution, applications, etc.

## Basic clues to understand extraordinary transmission metamaterials and scope of the talk

The cornerstone of the work is the array of subwavelength holes either free-standing or dielectric loaded. Roughly speaking, the mechanism behind the extraordinary (optical) transmission supported by this structure is: an incident electromagnetic wave couples to a complex surface wave (surface plasmon polariton at optics, leaky wave in those ranges where metals behaves like perfect electric conductor like microwaves and millimetre-waves) because of the presence of the grating. Then, there is an evanescent coupling through the holes between input and output interfaces, generating a complex surface wave on the other face of the metal, which couples in turn by reciprocity to an outgoing plane-wave. If the grating relies over a dielectric slab, the density of states can be enhanced because of the addition of waveguide modes (grounded dielectric modes that can be either TM or TE modes) and the interaction between the leaky wave and waveguide modes can lead to anomalous extraordinary transmission (term coined by the Millimetre and Terahertz Waves Laboratory) and superluminal among other phenomena.

The next stepping-stone of the review is the stack of these subwavelength hole arrays. It is shown that for extremely close stacking, the dispersion diagram of the structure normal to the surfaces accounts for backward-wave or left-handed propagation, see Fig. 1. This propagation can be explained within the formalism of electroinductive waves, whose mechanism relies on the electrical coupling between resonators. The left-handed propagation, and thus, the effective negative index of refraction, is further numerically verified by retrieved constitutive parameters ($\varepsilon$ and $\mu$) and experimentally confirmed by interferometric techniques and pure geometrical experiments: wedge experiment (Fig. 1) and oblique incidence over a flat slab.

Finally, several applications of extraordinary transmission metamaterials are depicted. Particular emphasize is put on negative-refractive and near-zero index extraordinary transmission lens for beamforming (Fig. 2).

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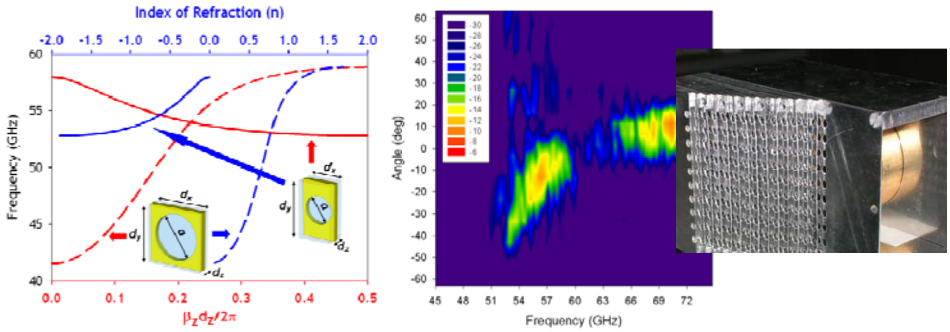


Fig. 1. (left) Dispersion diagram and index of refraction together with the corresponding unit cell. (right) Angular power distribution as a function of frequency. Inset: photograph of the prism.

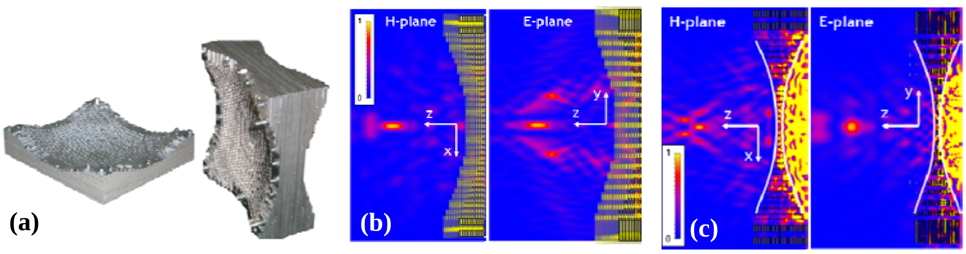


Fig. 2. (a) Plano- and bi-concanve extraordinary transmission lenses. (b) Simulated power density evolution along *xz*- (left) and *yz*-planes (right) for a plano-concave lens. (c) Simulated power density evolution along *xz*- (left) and *yz*-planes (right) for a bi-concave lens.